# TECHNICAL REPORT, FINAL

## Strain Partitioning in Los Angeles-Ventura Region, Southern California: Evidence from Precise Leveling across Active Folds

by

Arthur G. Sylvester

Institute for Crustal Studies and

Department of Geological Sciences

University of California, Santa Barbara

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Arthur G. Sylvester
Department of Geological Sciences, and
Institute for Crustal Studies
University of California
Santa Barbara, California 93106-9630
(805) 893-3156
e-mail arthur@magic.ucsb.edu

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Abstract Comparison of three first-order leveling surveys across Ventura Avenue anticline indicate that five bench marks on its crest increased from 10 to 40 mm in 19 years relative to its flanks, despite continued pumping of oil and water from the anticline. The cumulative seismic moment of all earthquakes in and near the anticline in those 19 years scarcely exceeds the equivalent of a M4 earthquake, which, if it occurred at the 12-16 km depths where the hypocenters are located, would be sufficient to cause only 10 mm of surface uplift. The five bench marks lie above an active oil field, suggesting that the height changes among the bench marks may be nontectonic due to injection of water that exceeded the volume of produced oil and water between 1980 and 1987. After 1990 the proportion of injected water was less, but the height change still increased at the same rate (2 mm/yr) even as it has been during at least the past 80,000 years. The location of the height changes at the crest of the anticline, their observed rate of change, and their positive sign, together with the general observation that subsidence, not uplift, happens above active oil fields, are permissive evidence that the observed height changes are tectonic. Relative to the contemporary 6-8 mm/yr horizontal shortening across the Ventura basin, the 1-2 mm/yr height change across the Ventura Avenue anticline suggests that from 10 to 20% of the regional crustal shortening is being released locally in the anticline as aseismic uplift. It is simplistic to conclude that such partitioning of strain thus decreases the size or frequency of future earthquakes by the same percentage, however, because the 19 year sample is small both temporally and areally for this part of the western Transverse Ranges.

# Introduction

## The Problem

It is generally believed that the earthquake process involves the abrupt release of elastic strain energy that has accumulated along a fault over some characteristic period of time since the last coseismic event (Schwartz and Coppersmith, 1984; Thatcher, 1984). In theory, then, one ought to be able to predict the sizes and times of the earthquakes by knowing the relation between the strain accumulation rate and the strength of the fault as well as the elapsed time since the last earthquake. Calculation of the strain budget is complicated considerably, however, if some proportion of that available accumulated strain is released *anelastically*, such as by fault creep or fold growth.

Anelastic behavior of the crust is difficult to recognize and quantify due to its generally small magnitude, commonly less than 1 mm/yr, perhaps spread over a large area. Anelastic behavior along faults may be manifested by fault creep, chiefly along strike-slip faults, in folded areas by imperceptible fold growth, and regionally by epeirogenic uplift. Geodetic methods measure and monitor current and historic deformation including and especially fault creep; geomorphic analyses provide approximate measures of anelastic deformation in recent geologic time, especially on the scale of mountain ranges.

This study focuses on growth of a single, though large and impressive fold in the south flank of the onshore part of the western Transverse Ranges. Its geologic structure is well known from extensive surface and subsurface studies. Its uplift history and rate are better known than most other anticlines in southern California from precise levelings since 1920 (Buchanan-Banks et al., 1975) and from tectonogeomorphic studies that extend the record back at least 80,000 years (Putnam, 1942; Rockwell et al, 1984). Regional horizontal GPS measurements have also been done extensions of the anticline in Ventura basin, 35 km to the east but covering only a four year period (Donnellan et al., 1993a, b) and over an 18 year period 30 km to the west (Larsen et al., 1993).

Proof of anelastic behavior in part of the Transverse Ranges would give reason to suspect that similar behavior may characterize similar youthful structures elsewhere in the Transverse Ranges, especially in the belt of folds and thrusts in eastern Ventura basin and along the north edge of the Los Angeles basin. There recent discoveries of youthful folds and faults led other investigators to postulate that the earthquake hazards are greater that previously estimated (Dolan et al., 1994), although that conclusion has been effectively refuted (Stein and Hanks, 1998), but if some of that deformation occurred and is occurring aseismically, then the hazard may be less. Just how much less is probably a function of the areal extent of anelastic behavior, and that will require considerable efforts to define in sufficient detail to estimate its effect in decreasing earthquake hazard.

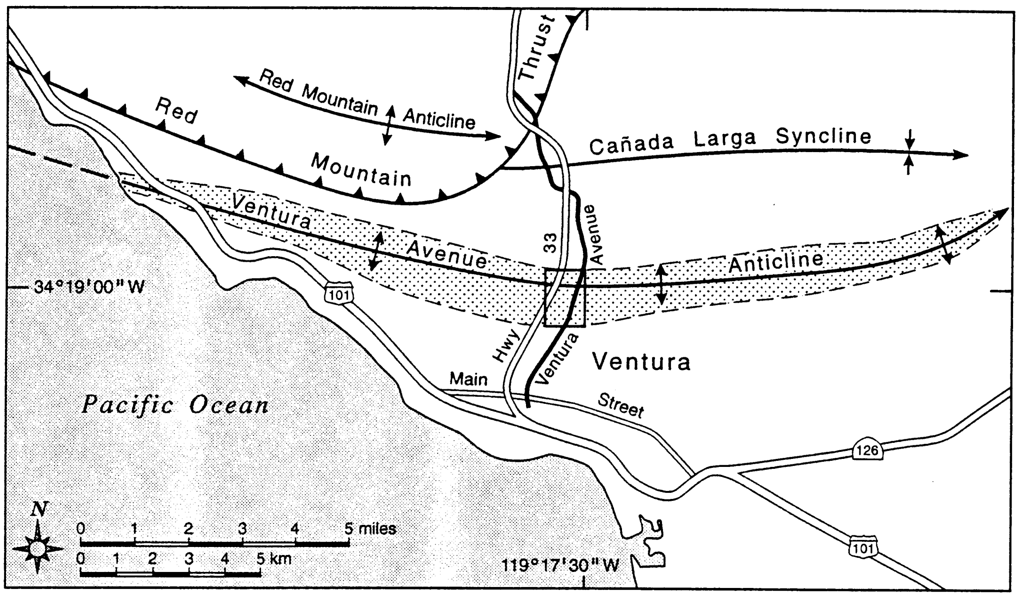


Fig. 1. Location map of Ventura Avenue leveling relative to Ventura Avenue anticline (shaded) and other folds and faults. Trace of anticlinal crest from Dibblee (1988).

### Geologic Setting and Structure

Ventura Avenue anticline (Fig. 1) is a geologically youthful fold in the western Transverse Ranges, a physiographic and structural province of east-west trending mountains, valleys, and geologic structures 100 km long and 40 km wide that extends eastward from the coast across the belly of southern California. The region is and has been undergoing active north-south crustal shortening in the last 5 Ma since being rotated 90°-120° clockwise and translated northwestward into its present position as a result of its capture by the Pacific plate from it initial position against the southwest edge of the Peninsular Ranges between Los Angeles and San Diego (Nicholson et al., 1994).

Structurally the anticline is an east-west trending, upright, symmetric, open fold (Fig. 2) with a gently dipping south limb and a steeper north limb (Dibblee, 1988). The anticline consists of a relatively thin-bedded succession of mostly interbedded sandstone and lesser siltstone Fig. 2) that was deposited at bathyal depths by turbidity currents in Pliocene time (Hsü, 1977). Sandstone beds are typically 0.5 to 2 m thick; interbedded siltstone and shale beds range from a few millimeters to as much as a meter in thickness. Where crossed by the Ventura River the amplitude of the fold is 1500 m relative to the adjacent Cañada Larga

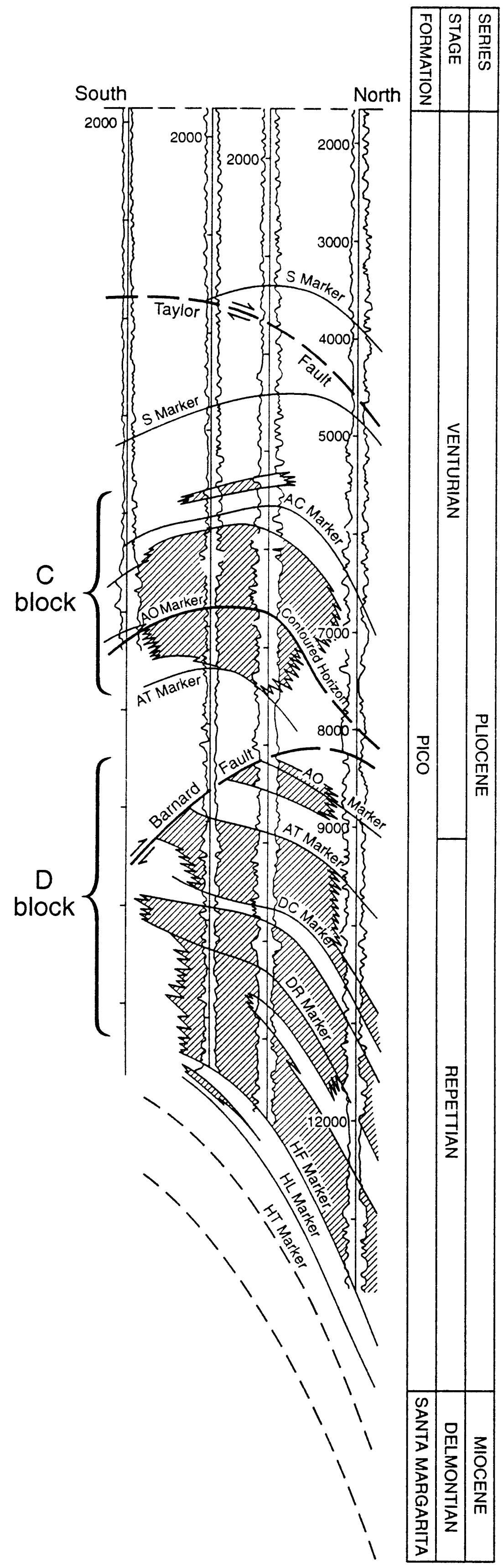


Fig. 2. Representative north-south cross section across Ventura Avenue anticline approximately 3 km east of Ventura Avenue, showing relation of producing zones C (between Taylor and Barnard thrusts) and D (below Barnard thrust). Electric logs indicate the high proportion of sandstone relative to siltstone. Based on data from AAPG, Pacific Section, Cenozoic correlation section across central Ventura basin, 1956, and modified from California Division of Oil and Gas (California Division of Oil & Gas, 1991, p. 572).

syncline, judging from cross section extrapolations (Dibblee, 1988; 1992; Yeats, 1983). The fold's radius of curvature decreases with depth, and folded, high-angle reverse faults having separations of less 200 m occupy its core (Fig. 2; Yeats, 1983; Grigsby, 1988). Folding is assumed to have been accomplished by flexural slip (Grigsby, 1988). The fold is a major trap for petroleum and has yielded nearly a billion barrels of 25-33 API-gravity oil to 1989 since the oil field was discovered in 1917 (CCCOGP, 1991).

The Pliocene beds are locally overlain unconformably by fluvial terrace gravels deposited by ancestral stages of the south-flowing Ventura River. Those terrace deposits on the south limb dip gently southward, whereas those on the north limb locally dip gently northward and, therefore, have been tilted against the present, and presumably past, stream flow direction (Putnam, 1942). The 759,000 yr BP Bishop Tuff is also interbedded in the succession with more than 1000 m of marine shale and siltstone above it (Sarna-Wojicki, et al., 1991). Both the tuff and the shale/siltstone participated in the folding and subsequent erosion, and both are overlain unconformably by a marine terrace deposit assigned to the lower part of the Saugus Formation, which is either 500,000 yrs BP or 200,000 yrs BP (Huftile and Yeats, 1995).

The fold began to grow in just the last 200,000-500,000 years (Rockwell, et al., 1988; Grigsby, 1988). At first the fold height increased rapidly (about 5 mm/yr) and slowed logarithmically to 2 mm/yr (Rockwell, et al., 1988), which is the rate observed in this study over the past 20 years . At a steady rate of 3 mm/yr, a fold will grow to an amplitude of 1500 m in 500,000 years, consistent with the geologic rates determined by Rockwell et al (1984). It is noteworthy that the anticlinal trap formed, the oil was generated, and it migrated into the structural - all within less than one-half million years.

Nowhere on and around the surface of the fold is there evidence of fault line structural damage that one would expect from surface fault creep or folding of the kind observed along faults in the Los Angeles area, or of the kind that is associated with strike-slip faults in central California. But if folding occurs at an uplift rate of only a few millimeters a year over a broad area, then ensuing damage may not be noticeable at all. This study tests the hypothesis that at least some of the horizontal strain is being released anelastically by broad-scale folding.

**Previous Geodetic Work**

Two principal leveling routes were established decades ago on or around the anticline. One is along the coast highway on the south flank of the fold, nearly parallel to its axis in a position that is relative insensitive to tilt and growth of the anticline (Fig. 1). The other is in a nearly north-south line along Ventura Avenue, transverse to the fold axis.

\Ventura Avenue lies in the water gap carved across the fold by the south-flowing Ventura River.

Control surveys were done of both lines in 1900/01, 1920, 1934, 1939, 1960, 1968, and 1971. The observed elevations from those surveys were orthometrically corrected, the more recent data were corrected for temperature variations and for rod and instrumental biases, and the levelings were compared with one another to determine regional elevation changes (Buchanan-Banks *et al.*, 1975). The principal result was demonstration of 10-14 mm/yr differential subsidence across Ventura Avenue anticline between 1934 and 1960 (Fig. 3), caused, ostensibly, by the withdrawal of oil, gas, and water from the oil field.

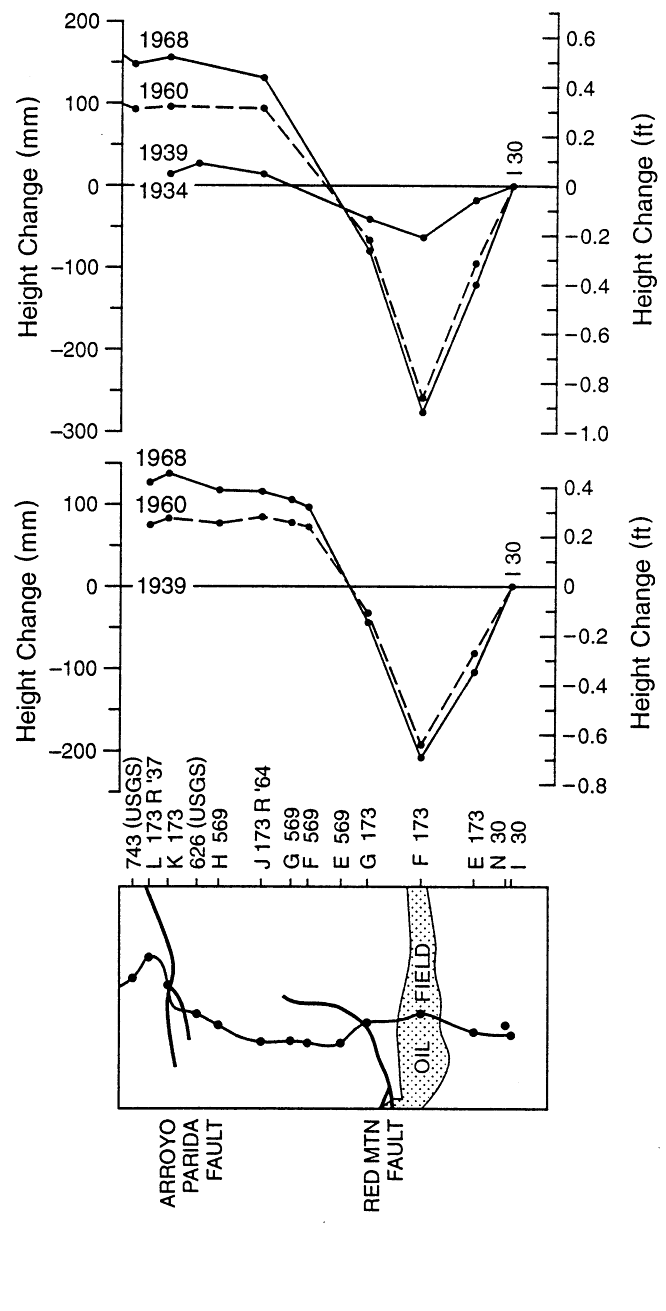


Fig. 3. Profiles of observed height changes of bench marks along Ventura Avenue, 1901-1968. Bench mark I30 is held invariant (after Buchanan-Banks et al., 1975).

By state law, however, produced fluids must be replaced to mitigate potential subsidence, and comparison of the 1960 and 1968 levelings (Buchanan-Banks, *et al.*, 1975), a decade after the law went into effect in 1956, indicates that a re-injection program was successful in countering local subsidence. Thus the 1960 and 1968 leveling profiles are virtually identical across the anticline in spite of major production of fluids from the oil field (Fig. 3).

### Horizontal Strain

The amount and rate of horizontal shortening is not known across Ventura Avenue anticline itself. GPS measurements across the eastern Ventura basin, 35 km east of the anticline, between 1988 and 1992 yielded north-south shortening of 8.5 mm/yr (Donnellan *et al.*, 1993a, b). About the same distance to the west, a combination of GPS and laser ranging measurements yielded a north-south shortening rate of $6.4 \pm 0.9$ mm/yr across the Santa Barbara Channel between 1970-1988 (Larsen *et al.*, 1993). Other determinations of shortening across Ventura basin are estimations and range from 9-10 mm/yr, based on flexural slip modeling of the Ventura Avenue anticline and summation of fault slip west of the San Andreas and San Jacinto faults (Rockwell, 1988; 1994), to $10 \pm 3$ to $14 \pm 1$ mm/yr based on retrodeformation of cross sections with the top of the Saugus Formation regarded as 500 ka (Huftile and Yeats, 1995).

### Seismicity

A band of earthquake epicenters follows the axis of the Ventura Avenue anticline throughout the length and breadth of the oilfield in the period 1978-1997 (Fig. 4). Most of the earthquakes are small, less than M 2.8, and they are relatively deep - 12-16 km - as deep as the deepest oil production, but nowhere near as deep as the regional décollement postulated to lie some 25-30 km beneath the anticline (Huftile and Yeats, 1995).

The cumulative seismic moment of all earthquakes in and near the anticline from 1978 to 1997 scarcely exceeds the equivalent of a M4 earthquake, which, if it occurred at the 12-16 km hypocentral depths, would be sufficient to cause only 10 mm of the 40 mm of observed surface uplift (O'Connell et al, 1997). This the basis for concluding that the bulk of the observed 40 mm of fold growth is aseismic.

## Leveling Bench Marks, Methods, Standard Error

### Bench Marks

The US Coast & Geodetic Survey established bench marks along the avenue in 1900/01 (Buchanan-Banks *et al.*, 1975) as part of the national vertical control network.

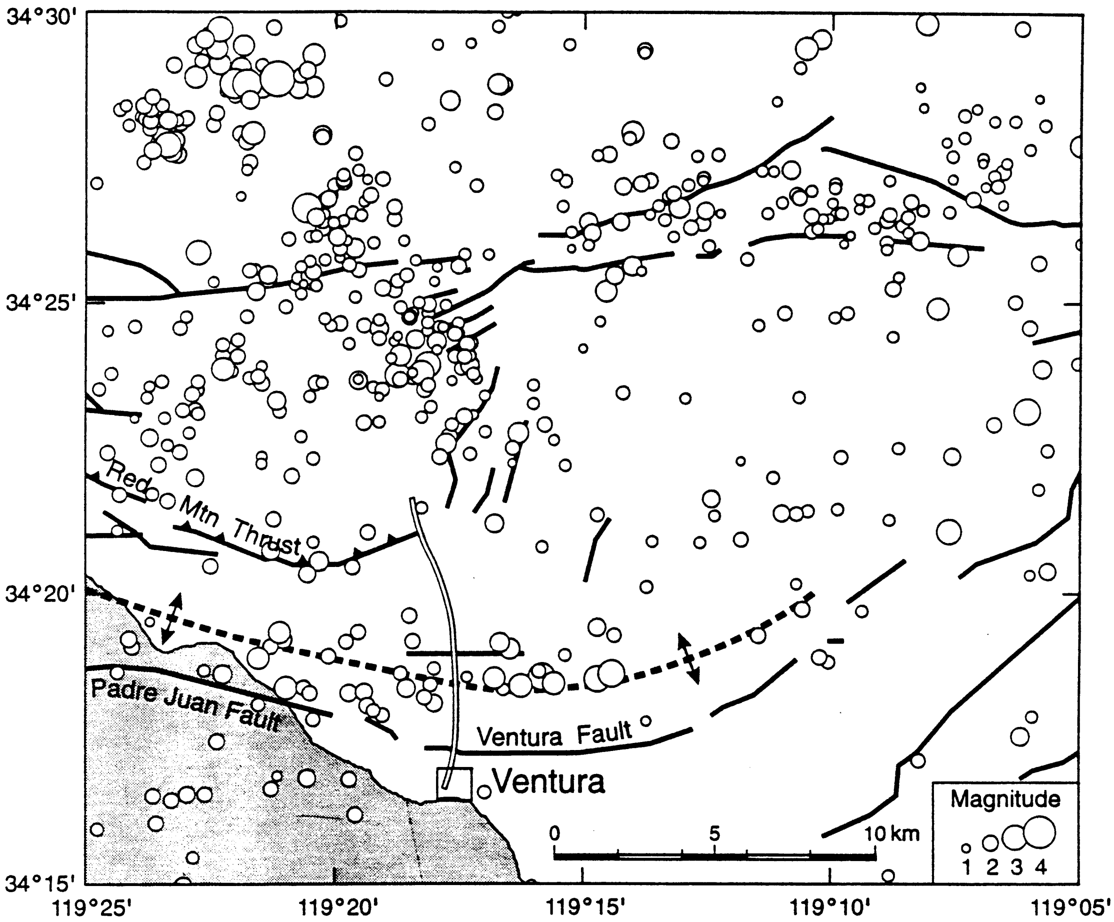


Fig. 4. Ventura region seismicity 1978 to 1997. Most activity is north of Red Mountain thrust. A diffuse linear grouping of small earthquakes is located along the mid-section of the Ventura Avenue anticline (dashed line).

Only three of those bench marks were extant in 1997, and one of them (I 30) at the coast is in a concrete caisson, but undercut by wave erosion, tilted, and therefore unusable since 1991. The Coast & Geodetic Survey established another set of bench marks in 1934, but only four of them are extant and usable today. The U.S. Geological Survey established a third set in 1973 that was surveyed by the National Geodetic Survey in 1978; all of the marks were recovered in good condition and re-surveyed by the County of Ventura in 1991 and by UCSB in 1997. All of the 1920, 1935, and 1973 bench marks are standard 10 cm-diameter, bronze disks. Some County of Ventura and private bench marks of miscellaneous design are also along the leveling route and were surveyed in 1997 (Appendix 1). Total length of the line surveyed in 1997 is 8850 m, incorporating 18 bench marks that were extant in the 1978 and 1991 surveys.

The 1997 leveling commenced on County of Ventura bench mark I6-100 at the northeast corner of Ventura Avenue and Harrison Street, because it is the farthest bench mark from those on the fold crest shared in the 1978 and 1991 surveys. The leveling route proceeded northward along Ventura Avenue, locally on the east side of the street, locally on the west. It crossed the crest of the anticline at bench mark 67FMK, crossed the Red Mountain thrust approximately between bench marks G173 and 74FMK, and continued northward up the avenue to the point where Ventura Avenue merges with State Highway 33 at bench mark E569 (Fig. 1).

Many of the bench marks are in culverts and curbs. Some are in massive pedestrian undercrossing foundations (P1048), small lightpole foundations (87-2), and concrete box culverts (68FMK, 87-4, 72FMK, 87-5, G173, 75FMK, E569, 87-7); only two are set in bedrock (65FMK and E569). In general, the stability of bench marks in curbs is suspect (Karcz *et al.*, 1976), but repeated leveling of the Ventura bench marks indicates that most of them are stable, the principal exception being G173 (Fig. 5), which is set in the edge of a small, concrete box culvert.

**Standards**

A Leitz NA-3000 digital level[1] (serial no. 89899) with matching pair of 3 m-long, strut-supported, bar-coded, invar leveling rods, 9505 and 9511, respectively, were used throughout the 1997 survey done by University of California, Santa Barbara, students and by Grimes Surveying. The rods were calibrated by automated laser interferometry in April 1992 at the Geodetic Institute, Technical University, Munich, Germany.

The 1991 survey was conducted by the County of Ventura Department of Public Works. The County used a Zeiss Ni2 precise level (serial no. 147204) with Wild GPL-3 invar paired rods 1093A/B, calibrated by the U.S. Navy Gage and Standards Laboratory, Pomona, in December 1989. The Zeiss Ni2 is known to be prone to a systematic error due to its magnetic compensator.

A Wild N-3 tilting level (serial #106101) owned by Ventura County was used in the 1978 survey together with Wild GPL-3 invar rods, serial numbers 1093A/B. These standards are approved for first-order precision leveling.

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[1]Mention of a commercial company or product does not constitute an endorsement by the University of California, the U.S. Geological Survey, or the National Earthquake Hazard Reduction Program. Use for publicity or advertising purposes of information from this publication concerning proprietary products or the tests of such products is not authorized by the author.

## 1997 Surveying Methods

The 1997 leveling was performed by closing a series of double-run loops from 0.5 to 3.5 km in length that consisted of foreward and backward observations of all bench marks within the loop. Shot lengths from instrument to rod were balanced, were less than 25 m, and averaged 20 m. The instrument was always shaded, and a temperature reading was taken at the instrument for nearly every shot at a height from 1 to 1.5 m above the ground surface, although the temperatures were not used in data adjustment. The A-rod was always placed on a permanent bench mark to minimize errors due to differences in rod length. To minimize personnel errors, each instrumentman shot the backrun of his forerun.

From three to five readings (about 30 scans each) are recorded automatically by the NA-3000 digital level, generally yielding a standard deviation of less than 0.10 mm (Arabatzi et al., 1993). Data for a leveled section were rejected and rerun if the forward and backward runnings of a section between two permanent bench marks differed by more than $aL^{1/2}$, where L equals the segment length of that section in kilometers.

The leveling data were recorded manually and preliminary closure errors were calculated in the field. Closure errors and relative bench mark heights were recalculated at the end of each day to check for errors in the field notes. We also searched for elevation dependent errors using the method of Stein (1981) and found the surveying was not plagued by such errors, because of the short shots (<25 m) we used. All the data were checked by an bug-free computer application that we have used for 20 years.

## Standard Error

The standard error, $\sigma_S$, of a single measurement was calculated using the method of proportionality [*Bouchard and Moffit,* 1965]:

$$\sigma_s=\sqrt{\sum\left(\frac{d_1}{2}\right)^2+\left(\frac{d_2}{2}\right)^2+...+\left(\frac{d_n}{2}\right)^2} \qquad (1)$$

where d = the misclosure for an individual survey segment in centimeters. For the purposes of calculating the standard error, we may consider the leveling route as two segments: I6-100 to N1048 and N1048 to E569. Misclosures the those segments are 2.9 mm, and 2.2 mm, respectively, respectively, yielding a standard error of 1.4 mm, which is reasonable and acceptable for the NA-3000 digital level. This value has been doubled in Figure 5 to depict two standard deviation "error bars" for the 1997 survey. Standard errors for the 1991 and 1978 surveys have not been so calculated, because we lack their field

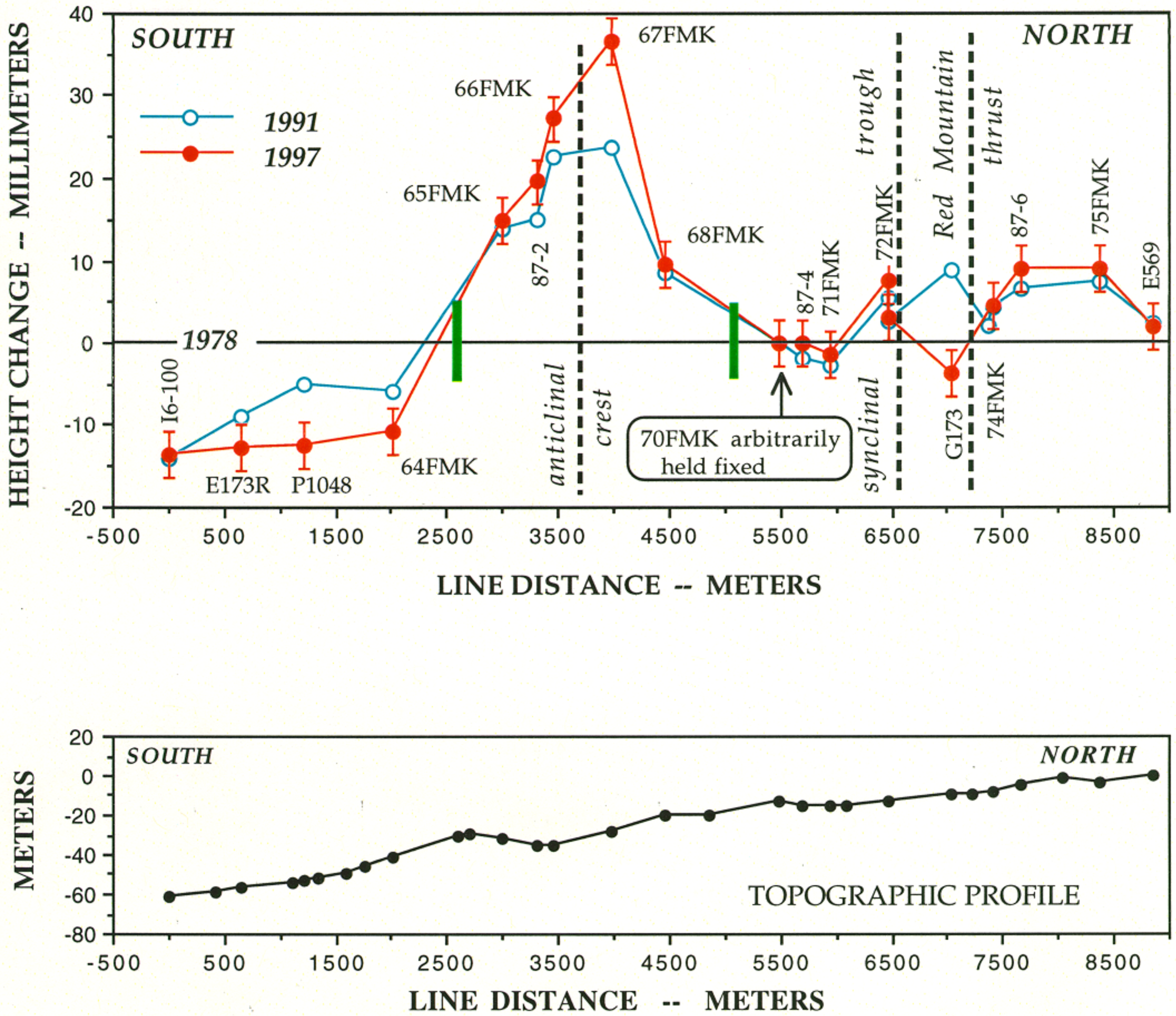


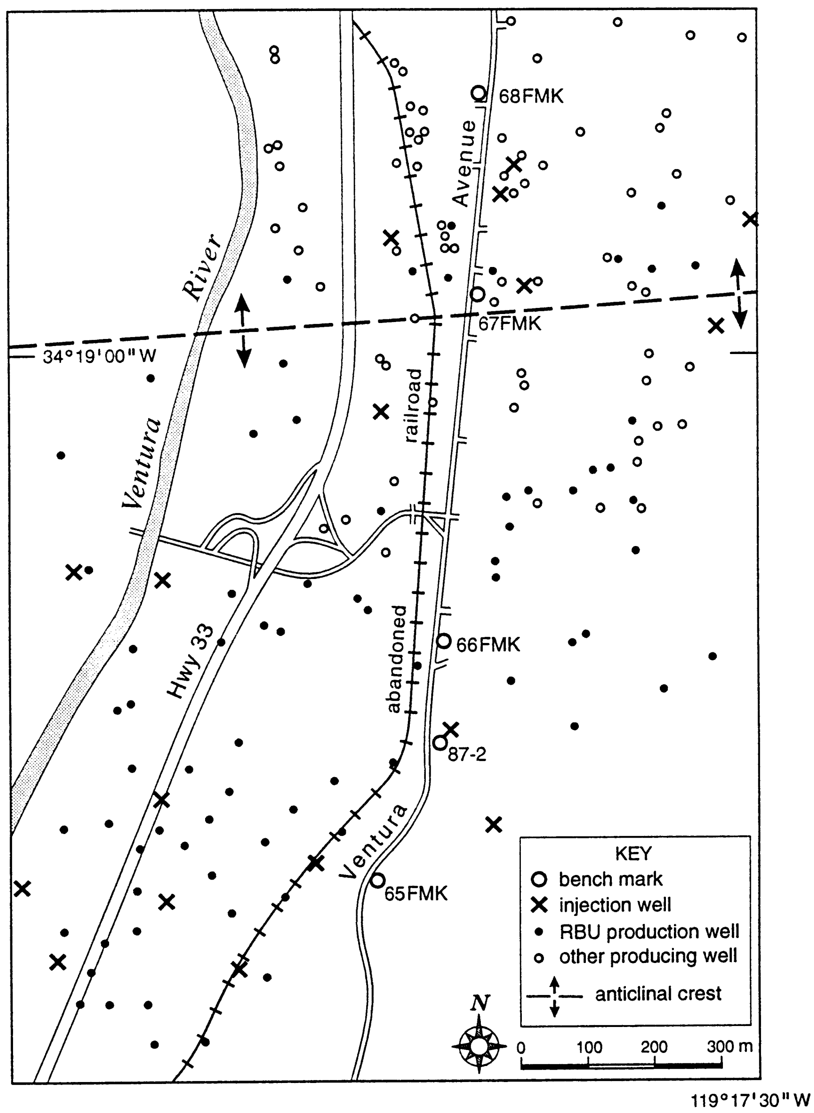

Fig. 5. Height Changes of 18 bench marks along a 9 km-long stretch of Ventura Avenue, 1978 to 1997, and topographic profile made from all bench marks surveyed in 1997. Error bars represent two standard deviations. Green bars indicate north and south limits of oil field. Bench mark 70FMK is arbitrarily invariant in this analysis after trials with several others, because its selection minimizes the height differences among most bench marks in the line among the 1978, 1991 and 1997 surveys and especially those in bedrock (65FMK and E569).

abstracts that would otherwise provide segment lengths and misclosures. Because both surveys are classified as "first-order" by NGS, we may expect that the standard errors are comparable to the UCSB 1997 survey, and therefore, it is justifiable to compare the bench mark heights from survey to survey.

## Surveying Results

Five of the 18 bench marks common to all three surveys rose from 10 to 40 mm relative to the other 13 (Fig. 5). One of those five bench marks is in bedrock (65FMK). Those bench marks bracket the crest of the anticline and lie within the limits of the oil field (Fig. 6). Although the data in Figure 5 are presented with bench mark 70FMK arbitrarily

Fig. 6. Map of bench marks (larger open circles) relative to producing RBU wells (solid dots), injection wells (crosses) within production limits of the anticlinal crest of Ventura Avenue oilfield. Compiled from California Division of Oil & Gas file data.



held fixed, the *pattern* of height changes remains the same, no matter which bench mark is held fixed: That is, the five bench marks on the crest of the fold rose relative to those on the flanks of the fold.

One may wish that absolute elevation changes could be presented in this analysis to answer the question, did the crest of the anticline actually rise relative to sea level, or did the flanks subside? An analysis of absolute motion requires tying the leveling data into sea level, commonly by reference to a tide gauge, the nearest of which is Tidal 8 in San Pedro, by GPS, or by absolute gravity. Indeed, the observed height changes are nearly large enough to be determined in successive surveys by GPS, but the first GPS observations in this line were only in 1997. Therefore, only height changes relative to an arbitrarily chosen bench mark are relevant in this discussion.

**1978-91 Height Changes**

Comparison of the 1978 and 1991 leveling surveys reveals that the crest of Ventura Avenue anticline rose nearly 25 mm relative to bench mark 70FMK on the north flank of the anticline (Fig. 5). The eight bench marks north of 70FMK, that is, those in the Cañada Larga syncline and around the Red Mountain thrust, differ nonsystematically from their 1978 positions by as much as 8 mm. The height of E569, in bedrock at the north end of line, changed negligibly between 1978 and 1991. The heights of four bench marks at the south end of the line decreased 5-15 mm relative to 70FMK. Those four bench marks are located in an industrialized stretch of Ventura Avenue that is built on Quaternary river terrace (Dibblee, 1988).

**1991-1997 Height Changes**

The height of the anticline increased an additional 5 mm from 1991 to 1997, again relative to bench mark 70FMK about 2000 m north of the crest of the fold (Fig. 5). Bench mark 67FMK rose about 10 mm more than its crestal companion, 66FMK, and about 13 mm relative to its position in 1991. The relative changes in among other bench marks in the north part of the line are negligible, being mostly within two standard deviations of the 1997 values, except for G173 which may imply instability of its small, box culvert fundament. The height of E569 in bedrock changed negligibly from its 1978 and 1991 positions.

The heights of four bench marks at the south end of the line decreased an additional 5-10 mm relative to their positions in 1991, but recall that three of the four bench marks are in curbs. Even so, I6-100 changed little from its 1991 height relative to 70FMK. P1048 is in a massive abutment for a concrete pedestrian undercrossing and might be expected to be the most stable of the four bench marks, and so be the best indicator of tectonic displacement, unless it as well as its adjacent bench marks are reacting to nontectonic subsidence induced locally perhaps by natural desiccation of the river terrace or pumping of groundwater by city or commercial interests. The stability of bench mark I6-100 between 1991 and 1997 would seem to belie the desiccation hypothesis.

## Discussion

### Effects of Fluid Withdrawal

It is mandatory in any discussion of height changes, especially in and around an active oil field, to evaluate the possibility that those changes have nontectonic causes. Nontectonic subsidence is common above exploited shallow aquifers such as those beneath Mexico City (Leggett, 1973, p. 464), Houston, Texas (Holzer et al., 1983, Holzer, 1990), Casa Grande, Arizona (Jachens and Holzer, 1979; 1982), the southern San Joaquin Valley, California (Holzer, 1980), and over oil fields such as Wilmington at the southwest edge of the Los Angeles basin (Gilluly and Grant, 1949), and Lake Maracaibo, Venezuela (Febres, 1989; Murria and Leal, 1992). In both of these oil fields, the measured subsidence has exceeded 6000 mm, compared to the cumulative, pre-1956 subsidence over Ventura Avenue oil field of only about 260 mm (Buchanan-Banks, 1975; Fig. 3). 260 mm of subsidence is not much in an oil field that has yielded nearly 1 billion barrels of oil and probably more than double that amount of water. The Wilmington oil field, comparable in size to Ventura Avenue, has produced about 3 billion barrels of oil, and has recorded cumulative subsidence of 10 m as of 1970 (Allen, 1973). Although the subsidence slowed or stopped within one or two years from the start of injection in the Wilmington field (Strehle, 1987), fluctuations of tens of centimeters can be predicted and caused today by varying the balance between fluid production and injection (Colazas and Olson, 1982; Strehle, 1987).

Typically the exploited stratal volume beneath subsiding oil fields consists of shallow, unlithified or poorly lithified, very porous reservoir rocks and overburden lacking self supporting structure, and from which large volumes of fluid have been extracted (Strehle, 1987). At Wilmington, for example, the shallow production zones are only 600-1000 m deep, the porosity is as high as 30%, the permeability of the principal exploited stratal zone is 1600 md, and the lithification is so poor that production of sand that constitutes the reservoir rock is a major problem (Table 1). The mechanism of subsidence involve reduction in reservoir fluid pressures by overpumping, causing increased grain-to-grain loading and compaction through repacking and rearrangement of grains, plastic flow of soft, intergranular constituents, crushing of grains, and elastic deformation of grains.

**Table 1. Comparison of Reservoir Properties, Wilmington and Ventura Avenue Oil Fields (from California Division of Oil and Gas, 1991)**

| | **Wilmington (Tar zone)** | **Wilmington (Ranger zone)** | **Ventura (C block)** | **Ventura (D block)** |
|---|---|---|---|---|
| Avg. Production Depth (ft) | 2200 | 2500 | 5180-7815 | 9150-10140 |
| Avg. Net Thickness of oil producing zone (ft) | 120 | 150 | 1170 | 660 |
| Porosity (%) | 32 | 32 | 18-20 | 17.0-17.6 |
| Permeability (md) | 1600 | 1638 | 48 | 20.0-22.3 |
| Oil gravity (*API) | 12 to 15 | 12 to 25 | 30 | 29-30 |

Overpumping of subsurface fluids does not necessarily cause ground subsidence in the overlying area. If the rock framework is well-lithified, if the porosity is relatively low, and if the production zone is deep - all of which factors pertain to the River Bottom Unit of the Ventura Avenue anticline (Table 1), then subsidence may be small or readily controlled by injection. In Memphis, Tennessee, for example, a decline in the artesian head of more than 30 m within confined aquifers of Eocene age has not resulted in any appreciable subsidence of the overlying ground (Leggett, 1973, p. 468).

### Ventura Avenue Oil Production

Oil was discovered in 1918 where the Ventura River crosses the anticlinal crest. Each of the main producing zones or blocks was discovered in the following decade. The production for the oil field as a whole amounts to more than a billion barrels as of 1997 together with twice that amount of water.

Production of oil, gas, and associated water from the Ventura Avenue anticline derives mainly from several production zones or blocks at depths ranging from 500 m to 6000 m (Fig. 2 and Table 1). Production from that part of the anticline beneath the leveling route has been from the C and D blocks at depths of 1730-3380 m, much deeper and from much stronger, less permeable rocks than at Wilmington (Table 1). Previously exploited from 13 separate leases, the C and D blocks were unitized in 1980, so that a single company may operate that part of the field as a unit, the so-called River Bottom Unit (RBU). Injection of produced water from the entire oil field commenced in C block in 1956 to counter subsidence and in D block in the late 1960s. Waterflooding intensified tenfold simultaneously in the RBU with unification in the early 1980s, and water still is injected under pressure into the oil producing zone. Some wells were converted into

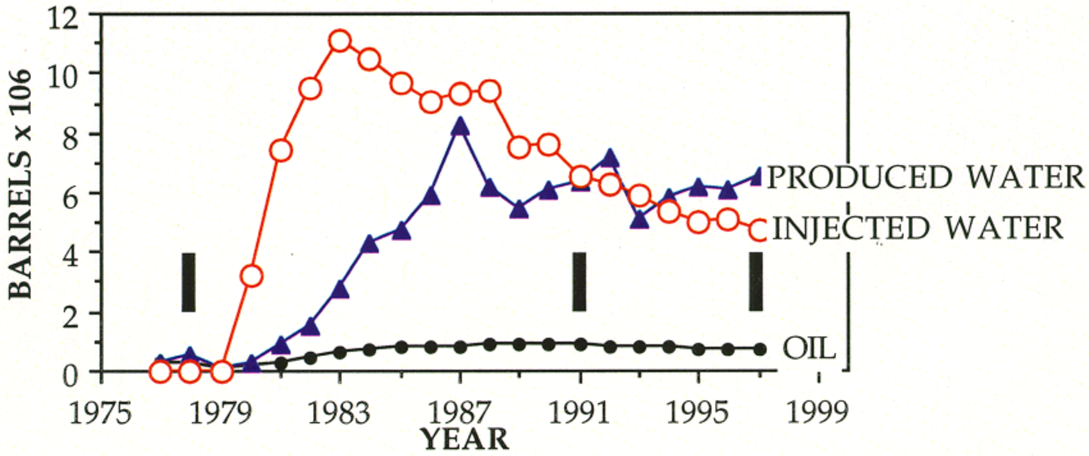



Fig. 7. Volumes of produced and injected fluids, River Bottom Unit, Ventura Avenue oil field, 1977 to 1997. Black bars indicate times of precise leveling surveys. Compiled from California Division of Oil & Gas file data.

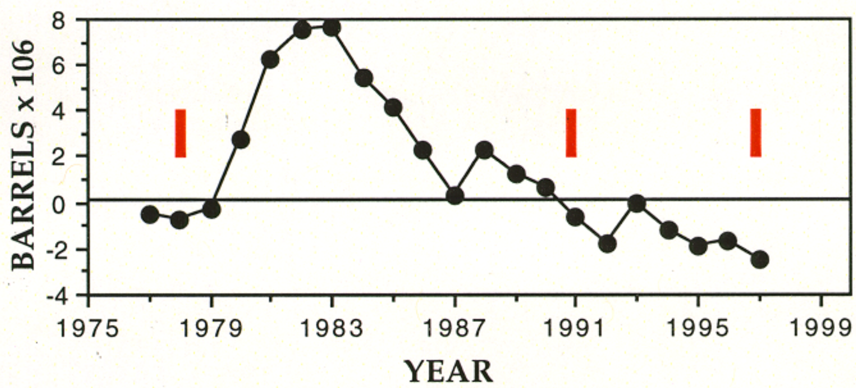



Fig. 8. Relation of injected fluids to withdrawn fluids, River Bottom Unit, Ventura Avenue oil field, 1977 to 1997. Red bars indicate times of precise leveling surveys. Compiled from California Division of Oil & Gas file data.

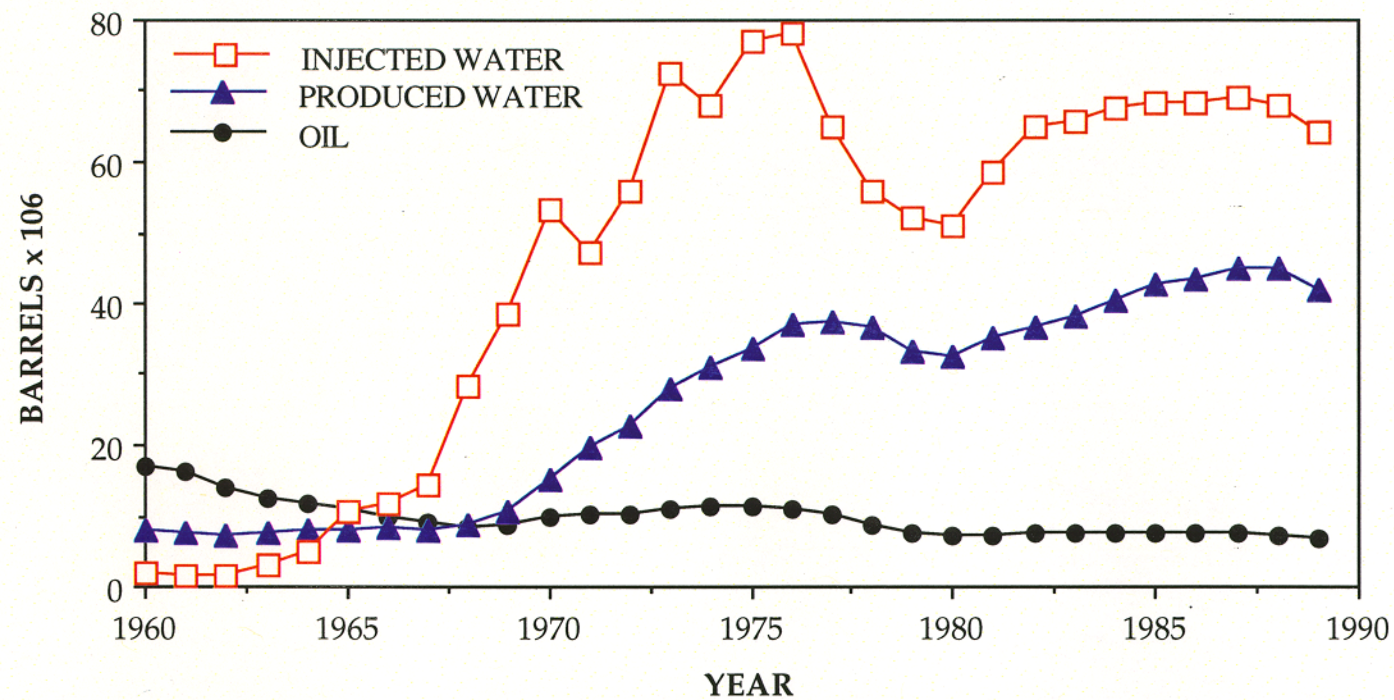



Fig. 9. Total produced and injected fluids, Ventura Avenue oil field, 1960 to 1989 (CCCOGP, 1991).

injection wells at that time, some wells were shut in, several wells were abandoned. Not only did oil production from single wells increase fivefold in many instances, but so also did production of water jump as much as tenfold (Fig. 7). No evident attempt has been made to balance fluid production *versus* fluid injection in the RBU (Fig. 8) or in the field as a whole (Fig. 9). In fact, only a single oil field in California, Wilmington oil field, is administered and closely monitored under the Subsidence Abatement Act (California Division of Oil & Gas, 1991, p. 594).

### Analysis of Ventura Avenue Subsidence

Buchanan-Banks et al (1975) concluded that three bench marks (E173, F173, and G173) subsided (75 mm, 260 mm, and 115 mm, respectively) between 1919 and 1960 on the Ventura Avenue anticline because of fluid withdrawal (Fig. 3). Only one of those bench marks, F173 (destroyed before 1978) was within the oilfield proper, however, and it was also within 100 m of several shallow oil wells that were subsequently shut in after 1978, except for some minor gas production from one well (Fig. 6). The subsidence rate of F173 was not great (about 7 mm/yr), and it is possible that all of its subsidence may be attributed to production from the nearby shallow wells rather than regarding it as a faithful recorder of the subsidence for the entire oil field. Bench mark 67FMK (Fig. 6), extant since 1974, is near the former location of F173.

The stability of the other two bench marks depicted by Buchanan-Banks (1975), E173 and G173, is also questionable (Fig. 5). Each is about 2 km south and north, respectively, of the anticlinal crest. E173 (destroyed and reset in 1974) was in a curb and G173 is in a box culvert, for both of which the vertical stability is suspect as mentioned above and discussed below. Therefore, it may be unjustifiable to blame the relative subsidence of these bench marks on withdrawal of fluids in the oil field. Buchanan-Banks et al (1975) also concluded that the subsidence was arrested after 1956 when the State of California required oil field operators to return as much fluid to the reservoir as was taken out, under the dictates of the Subsidence Abatement Act. That conclusion was made from their comparison of the 1960 and 1968 leveling surveys across Ventura Avenue anticline relative to net fluid production in the entire oil field (Buchanan-Banks, 1975; Fig. 3).

## Causes of the Height Changes

The observed relative height increase of five bench marks on the crest of the Ventura Avenue anticline from 1978 to 1997 may be attributed to one or combinations of the following factors:

1) surveying errors;

2) unstable bench marks;

3) inflation of reservoir by excess fluid injection relative to withdrawal;

4) coincidence of surveys to times when net production of fluids = 0;

5) tectonic growth.

**Surveying Errors**

We took exceptional care to perform the surveying according to specifications prescribed for first-order surveying (Federal Geodetic Commission, 1984). We searched our data for elevation dependent errors using the method of Stein (1981) and found such errors are lacking, probably because of the short, balanced shots (<25 m) we generally use (Castle et al., 1994). The double runs should have precluded field blunders.

The fact that the three surveys by three different groups match reasonably well indicates that the surveys are of comparable quality, and that any given survey is free of major errors. Surveying errors or blunders may be ruled out as contributory to the pattern of observed height changes.

**Unstable Benchmarks**

Visual inspection of each bench mark revealed no indication that any of the main bench marks depicted in Figure 5, especially the five on the anticlinal crest, were unstable or disturbed. Only G173, on top of a concrete box culvert, experienced a reversal in height change, of about -4 mm between 1978 and 1991, and about +10 mm between 1991 and 1997 (Fig. 5). Bench mark 87-2 is set in the concrete base of a light pole and, therefore, would not seem to be an especially stable fundament, but its height change from 1978 to 1991 is comparable to 65FMK set about 150 m to the south in bedrock, and from 1991 to 1997 its change is comparable to 66FMK (Fig. 5) set about 75 m to the north in the foundation of a concrete box culvert. Without many more surveys to provide comparisons, one must conclude that the bench marks are sufficiently stable for the purposes of this study.

**Reservoir Inflation**

Just as poroelastic stressing models predict slight increases in horizontal compressive stress above and below a draining reservoir, coupled with surface subsidence (Teufel et al, 1991; Segall and Fitzgerald, 1998; Rutledge et al., 1998), so also may *injection*-induced stress changes lead to tensile stress and reverse faulting above and below the draining reservoir, coupled with surface uplift. Slip on pre-existing faults is more likely than breakage of unfaulted rocks in such cases (Segall and Fitzgerald, 1998), and although the stress changes are small and may be insufficient to induce earthquakes in critically stressed crust, they may be sufficiently large to promote aseismic creep on favorably oriented faults within the anticline, such as the Barnard and Taylor thrusts (Fig. 2) with consequent uplift within the volume domain of the anticline.

Alternatively, the injection may reduce the effective normal stress across pre-existing faults by increasing the pore pressure, thus allowing the faults to creep, and to yield the uplift surface strain signal thereby that we see in the leveling data. Supporting this hypothesis is the fact that only those bench marks within the boundaries of the oil field have risen (Figs. 5, 6), and that the injected fluids were far in excess of the produced fluids in the RBU between the 1978 and 1991 surveys (Fig. 8). It was pointed out above that no attempt is made at Ventura Avenue to insure that the volume of injected fluids balances the withdrawn volume. Moreover, it is impossible to insure that the injected fluids will travel to and uniformly fill the drained parts of the reservoir; they may travel considerable distances laterally and vertically from the RBU. It would seem reasonable that calculation of the net imbalance between injected and produced fluids would permit calculation of the net surface strain of the RBU reservoir as an isolated domain within the anticline, but there is no guarantee that the resultant "model" will have any relation to reality.

### Coincidence

Because the number of surveys is few relative to the production history of the River Bottom Unit (Fig. 7), confident determination of the behavior of the oil field due to the waterflooding that commenced in 1980 is precluded. One may assert, for example, that the observed pattern of height changes is fortuitous and happens to coincide with the times when the volume of withdrawn fluids exceeded those injected (Fig. 8). We cannot know, for example, if the five bench marks at the crest of the anticline have fluctuated wildly but the levelings, widely separated in time relative to fluctuations in injection vs production, just happened to catch the bench marks when they were going through a nearly common point in space.

### Conclusion

The 20-40 mm height change of five bench marks in 18 years is small relative to the length of the entire leveling line or the cross axis dimension of the fold itself, but the magnitude and rate of the height changes observed in that time are nearly same as those determined by tectonogeomorphic analysis (Rockwell et al., 1988) for at least the last 80,000 years, and even for the last 500,000 yrs if the base of the Saugus Formation is 500,000 years old. If the height changes had been of opposite sign, then the straightforward conclusion would be that they represent subsidence almost certainly related to pumping in the oil field, simply because pumping has caused subsidence in this oil field in the past and has done so in many other fields as well. That the apparent uplift could have been induced by oil field pumping is also possible but is less probable, only because no other oil fields, except Wilmington where there has been a concerted effort to counteract subsidence, provide examples of uplift above an active oil field. Thus the location of the height changes at the crest of the anticline, their observed rate of change, and their positive sign, together with the general observation that subsidence, not uplift, happens above active oil fields, are permissive evidence that the observed height changes are tectonic.

Proof of this conclusion would require a more thorough correlation of the height changes *versus* the injection and production records. Such frequent leveling was not done in the past and probably won't be done in the future, but future GPS measurements may make more frequent monitoring of height changes across the anticline possible.

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## Appendix 1. Ventura Avenue bench mark heights (mm), 70FMK=0.

| Bench Mark | Cumulative Distance | 1978 Ht | 1991 Ht | 1997 Ht |
|---|---|---|---|---|
| J6-100 | -563 | | | |
| I6-100 | 0 | | -48.32600 | -48.32254 |
| 62FMKRM1 | 413 | | -45.88020 | -45.88265 |
| E173 RESET | 649 | -57.03400 | -44.29640 | -44.29776 |
| L7-100 | 1118 | -53.89500 | | -41.15743 |
| P1048 | 1217 | -53.14600 | -40.40580 | -40.41047 |
| Pacific 1 1/4 | 1337 | | | -39.38864 |
| 63FMKRM1 | 1585 | -49.15400 | -36.47270 | -36.47733 |
| 87-1RM1 | 1767 | | -33.17430 | -33.17710 |
| M7-100 | 1808 | | | |
| 64FMK | 2016 | -41.16600 | -28.42480 | -28.42790 |
| N1048RM1 | 2587 | | -18.40440 | -18.41380 |
| N8-100 | 2696 | | | -16.90743 |
| 65FMK | 2989 | -31.98100 | -19.21870 | -19.21794 |
| 87-2 | 3316 | -35.38000 | -22.61540 | -22.61148 |
| 66FMK | 3454 | -34.81200 | -22.04080 | -22.03633 |
| 67FMK | 3980 | -27.72100 | -14.94900 | -14.93607 |
| 68FMK | 4463 | -7.29300 | -7.30800 | -7.30694 |
| 87-3 | | | | |
| 87-3RM1 | 4854 | | -7.26870 | -7.26856 |
| 70FMK | 5493 | 0.00000 | 0.00000 | 0.00000 |
| 87-4 | 5698 | -2.30300 | -2.30530 | -2.30413 |
| 71FMK | 5936 | -1.96400 | -1.96720 | -1.96658 |
| VC-01 | 6082 | | | -2.47136 |
| 87-5 | 6460 | -0.54300 | | -0.53580 |
| 72FMK | 6461 | -0.54100 | -0.53790 | -0.53862 |
| G173 | 7036 | 3.34300 | 3.34230 | 3.33860 |
| CalDivHwys | 7218 | | | 3.89451 |
| 73FMK | 7370 | 5.06800 | | |
| 74FMK | 7407 | 5.02000 | 5.02490 | 5.02330 |
| 87-6 | 7660 | 7.45100 | 7.45860 | 7.45967 |
| 75FMK | 8037 | | 12.06490 | 12.06344 |
| 87-7 | 8372 | 8.81800 | | 8.82576 |
| E569 | 8849 | 12.74900 | 12.75300 | 12.74986 |

## Appendix II. Resurveys of Other Folds and Faults

### Durmid Hill

This line of 95 bench marks in 3658 m crosses the San Andreas fault and the crest of Bat Caves Buttes, one and one-half miles northeast of the Salton Sea (Fig. II-1). It was established in September 1985 to determine if the buttes, which surmount Durmid Hill, are rising due to shortening related to the transpression on the San Andreas fault. Fifteen partial or complete surveys have been done of the line to and including that on 30 June 1996.

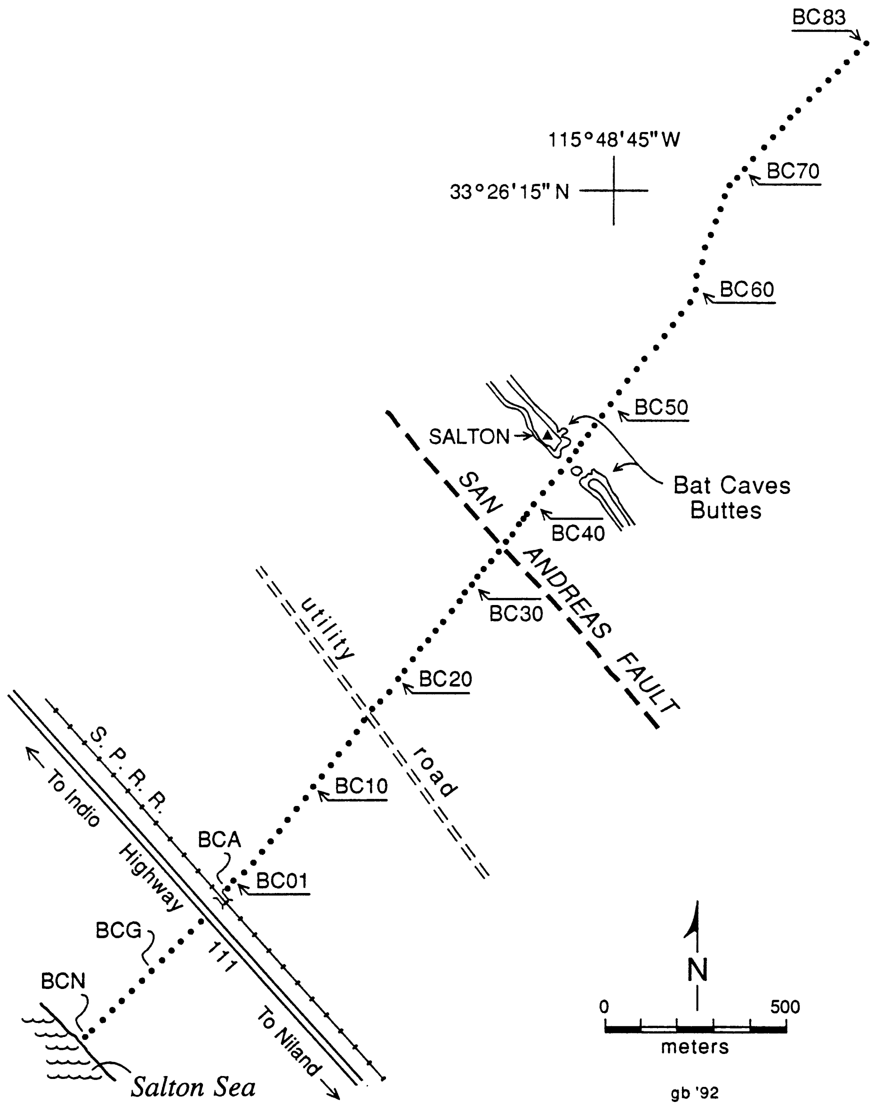


Fig. II-1. Site map of Bat Caves Buttes leveling array, comprising 97 permanent bench marks, across Durmid Hill, Coachella Valley, California.

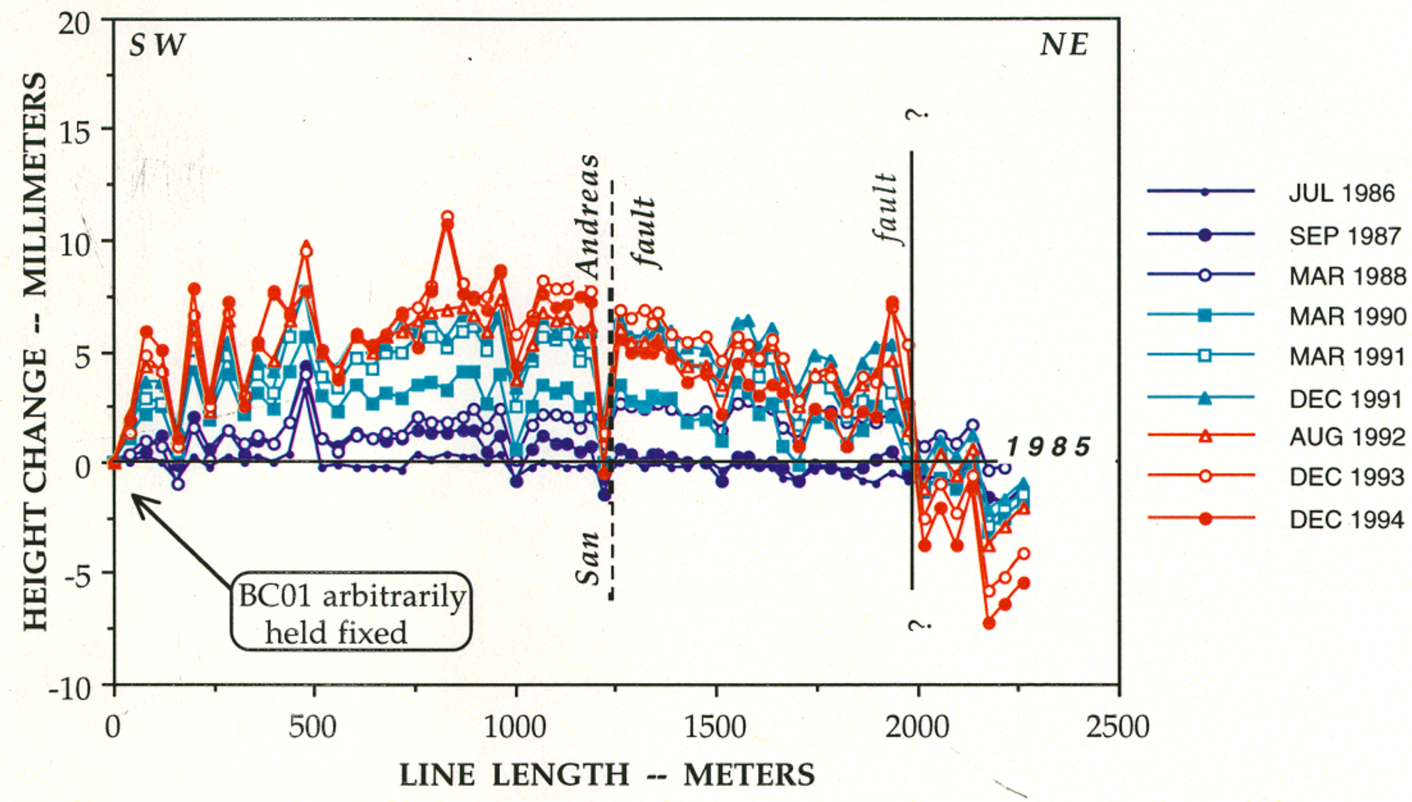


Fig. II-2a Height changes of bench marks in leveling line across Durmid Hill at Bat Caves, southeasternmost San Andreas fault, 1985 to 1992. Bench mark BC01 arbitrarily held invariant. From 1985 to 1992 the hill rose episodically at an average rate of 2 mm/yr (blue data), then it stopped after the 1992 Landers (M7.2) earthquake (red data), located about 100 km away.

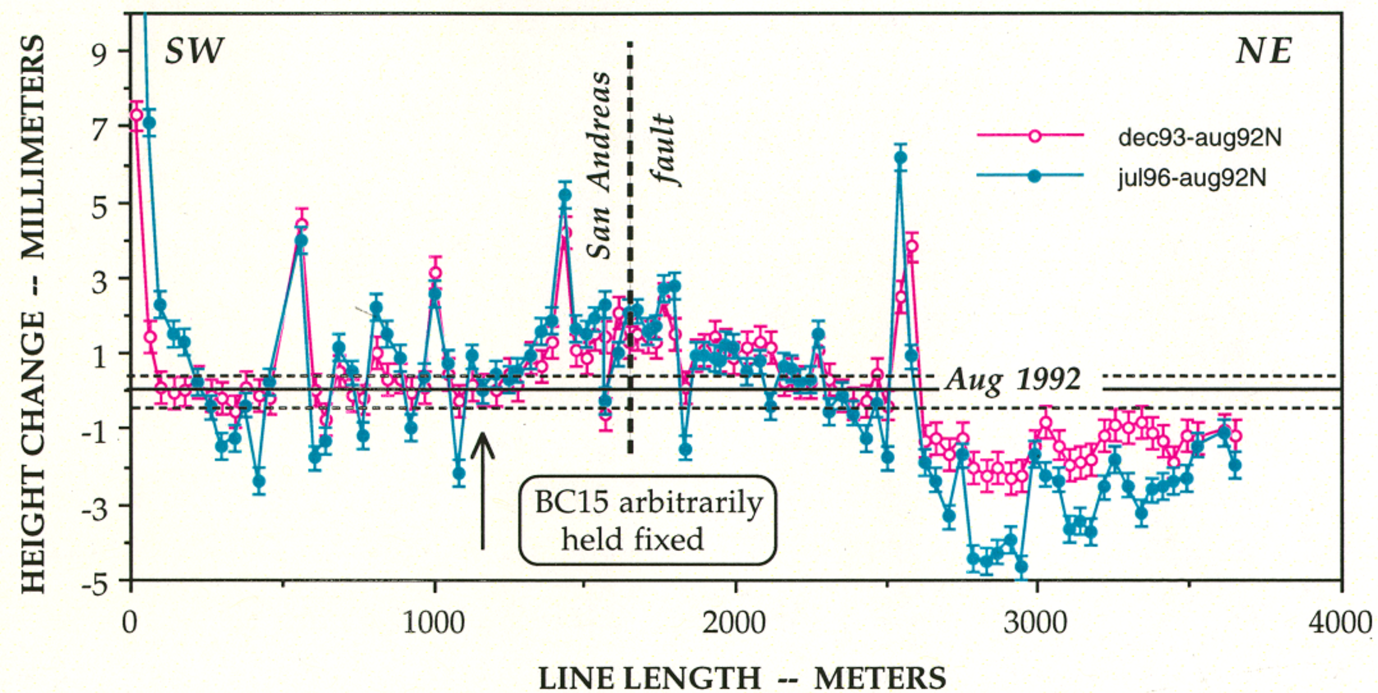


Fig. II-2b. Height changes of bench marks in leveling line across Durmid Hill at Bat Caves, August 1992 to July 1996. Line was lengthened in August 1992. Compare with Fig. II-2a. Bench mark BC15 arbitrarily held invariant.

From 9 September 1985 to 28 June 1992, Durmid Hill arched upward about 9 mm but not symmetrically relative to the crest of the hill (Fig. II-2a). Vertical displacement is not apparent across the San Andreas fault itself. The observed growth rate of the fold is consistent with the geologic rate of about 1 mm/yr of uplift determined from the inception of, and rate of downcutting of, Durmid Hill by Salt Creek and from tilting of ancient lake shorelines (Sylvester et al., 1993).

The leveling line was lengthened in March 1992 from 2268 m to 3658 m to define the inflection points of the uplift more completely. Since the Landers earthquake of 28 June 1992, Durmid Hill has ceased to rise (Fig. II-2b), implying that the strain field of the earthquake extended far beyond the region of surface rupture.

### Nebo

This line of 78 bench marks in 2962 m was established in 1994 to document folding across an WNW-trending anticline developed in Quaternary alluvium above an isolated and robust cluster of earthquakes related to, and at the northernmost end of, the 28 June 1992 Landers earthquake sequence (Fig. II-3). It was first surveyed in July 1994 and again in 1995 and 1996 (Fig. II-4). Bench mark NQ75 at the south end of the line was arbitrarily held invariant. Relative to the 1994 survey, the subsequent surveys indicate that the line has tilted northward roughly 1 microradian per year. If another bench mark were held invariant, such as almost any other one between the 1500 and 2000 m marks, then the data would suggest that the north flank of the anticline subsided about 2 mm between 1994 and 1995, and then it rose about 1 mm. The data yield no evidence of significant fold growth during the two years of monitoring the fold.

### Raymond Fault Crossing

This 10.2 km-long line across the Raymond fault in San Marino consists mainly of two generations of benchmarks established in 1934 by the Coast & Geodetic Survey, the 172-series marks, and by the U.S. Geological Survey in 1974, the FMK series marks. The line extends north-northeastward about 500 m from the northwest corner of Santa Anita Street and Las Tunas Drive in San Gabriel to its intersection with San Marino Avenue, thence about 1.5 km northward through San Marino on San Marino Avenue to its intersection with Sierra Madre Boulevard at Huntington Drive, thence about 3 km northward through San Marino and Pasadena on Sierra Madre Boulevard to its intersection with Altadena Drive about 50 m north of Foothill Boulevard, thence northward through Pasadena and Altadena on Altadena Drive about 7 km to the northwest corner of Eaton Canyon Park in Altadena near the intersection of Altadena Drive and Midwick Drive. The

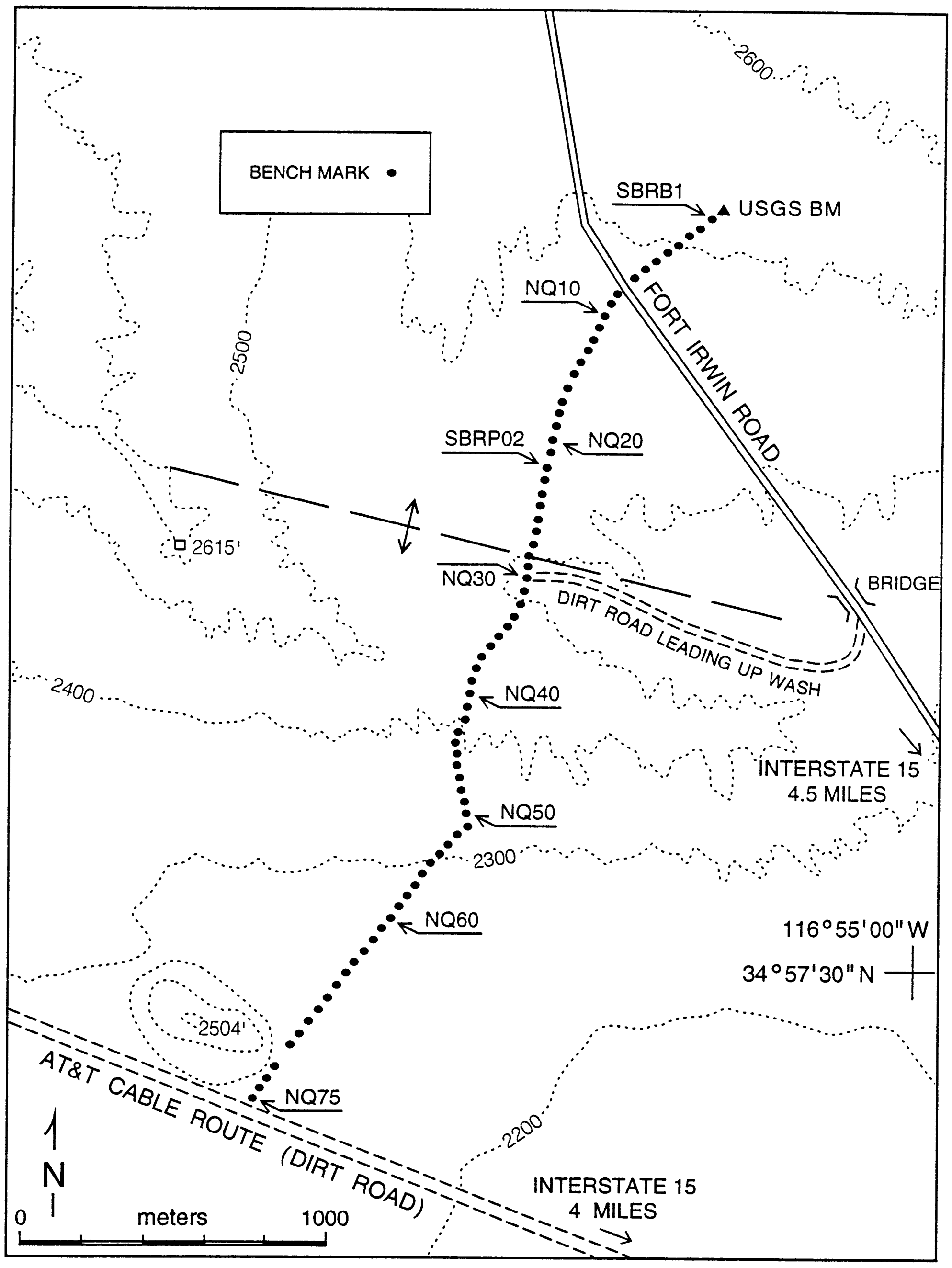


Fig. II-3. Site map of Nebo leveling array, comprising 78 bench marks, across Nebo anticline, 5 km north of Barstow, California.

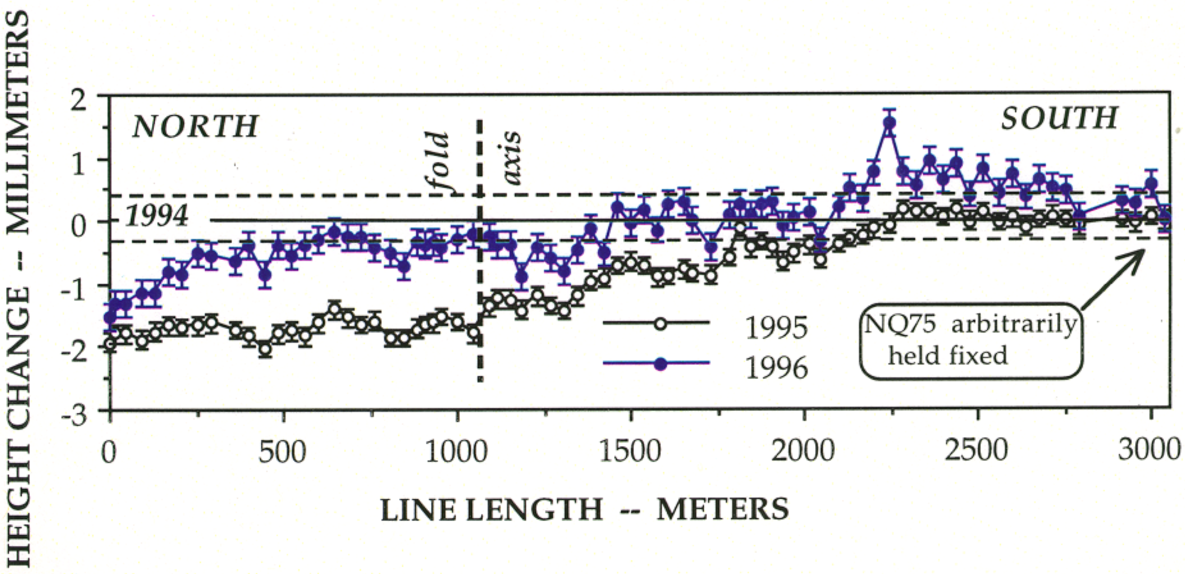


Fig. II-4a. Height changes of bench marks in leveling line across Nebo anticline. Bench mark NQ75 arbitrarily held invariant.

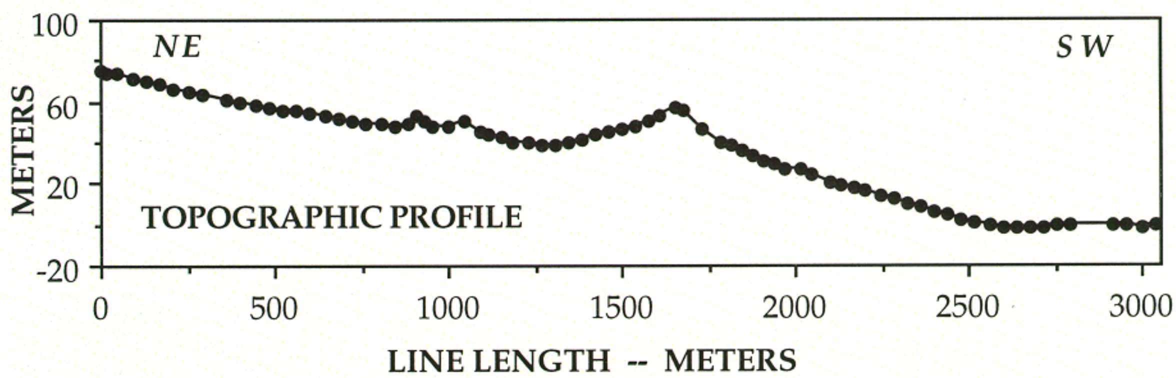


Fig. II-4b. Topographic profile along leveling line across Nebo anticline.

line crosses three strands of the Raymond fault between bench marks 63FMK and 64 FMK judging from the geologic map (USGS, 1987). It crosses a queried, buried strand of the Sierra Madre frontal thrust fault 200 km south of bench mark A174 at the north end of the line.

The only significant recorded earthquake on the Raymond fault during monitoring period, especially between 1974 and 1996, occurred on 3 December 1988 and had a $M_L$ of 5.0, but with a focal depth of 15.6 km, it produced no discernible surface deformation (SCEC, 1999a).

The 1996 leveling surveyed 24 bench marks, the last complete leveling of which was done in 1974 (Fig. II-5). Surveys of the 172-series bench marks were also done in 1961 and 1934. We arbitrarily held bench mark U172 invariant, because it is the only bench mark common to all three surveys.

The bench mark height changes are negligible across the Raymond fault zone from 1974 to 1996 (Fig. II-5). The 60 mm height change at the south end of the line is probably due to the fact that the curb containing P172 has been cracked and tilted. The 20 mm height change between 65 FMK and U172 has no ready explanation. The 75 mm height difference between U172 and A174 (Fig. II-5), both established in 1934, represents the height change between 1934 and 1996, equivalent to 8.3 mm/yr. Those years included several earthquakes, including the $M_W$ 6.6 1971 San Fernando earthquake, and the $M_W$ 5.8 1991 Sierra Madre earthquake on the Clamshell-Sawpit Canyon fault (SCEC, 1999b) that may have had a contributory effect upon the heights of the two bench marks, although no such effect was observed in UCSB's leveling line across the Sierra Madre fault in Santa Anita Canyon, 7.2 km east of this Raymond fault crossing line.

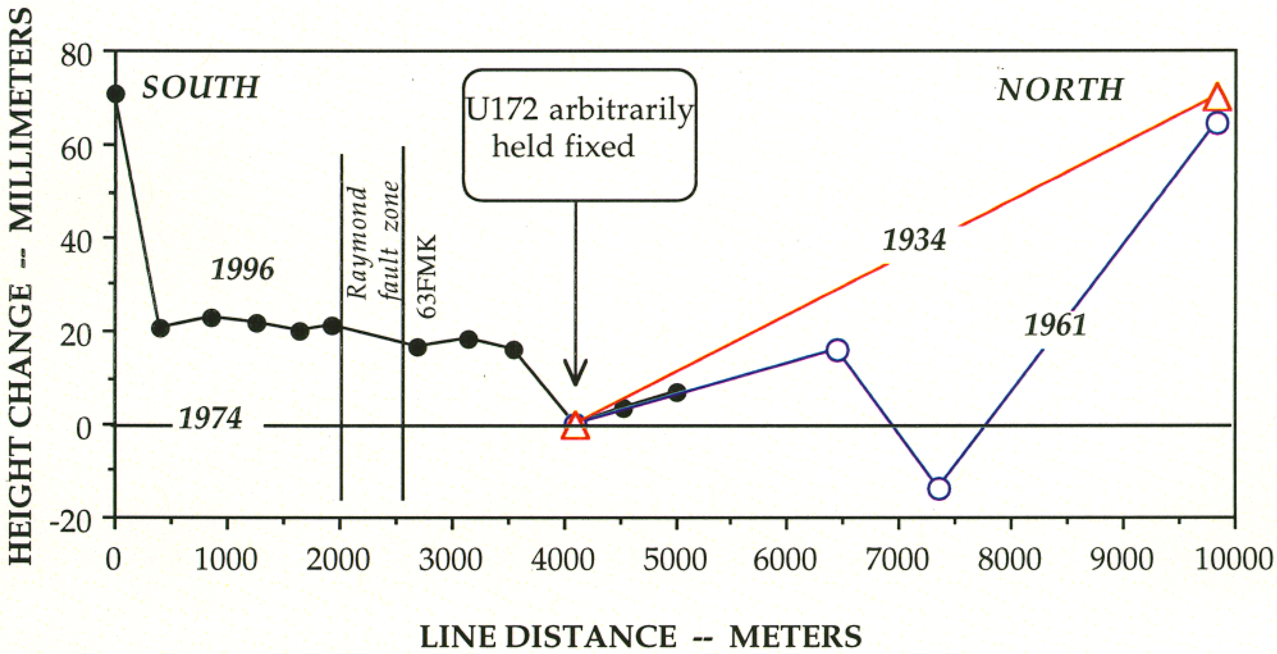


Fig. II-5. Height changes of 15 bench marks common to 1934, 1961, 1974, and 1996 levelings, along north-south line across Raymond fault zone and San Gabriel Valley from San Gabriel (left) to Altadena (right). U172 arbitrarily held invariant. Valley-down tilt indicated between U172 and north end of line since 1934.

## Concluding Statements

### Strain Partitioning

It was stated above in the main report that GPS measurements indicate that contemporary shortening is occurring across the Ventura basin part of the western Transverse Ranges at about 6 mm/yr west of Ventura Avenue anticline (Larsen et al., 1993), and about 8 mm/yr to the east (Donnellan, et al., 1993b). Relative to that 6-8 mm/yr shortening, the 1-2 mm/yr height change across the Ventura Avenue anticline documented of 19 years by this report suggests that from 10 to 20% of the bulk regional crustal shortening across the basin is being released locally in the anticline as aseismic uplift. It is simplistic to conclude that such partitioning of strain thus decreases the size or frequency of future earthquakes by 10-20%, however, because the 19 year sample is small both temporally and areally for this part of the western Transverse Ranges. As also mentioned above, Rockwell (1994) estimated that the *geologic* rate of shortening is in the range of 10-14 mm/yr, yielding, thereby, a lower proportion of the total bulk strain to assign to aseismic uplift. It is also simplistic to allow the GPS measurements across the Santa Barbara Channel and across the eastern Ventura basin to represent the total horizontal strain across the entire western Transverse Ranges, because several important active faults and major, probably still active folds were not crossed by the GPS measurements. Even the leveling data presented in this report (Fig. 5) indicates that the entire 9 km-long leveling line tilted 1-2 microradians down to the south between 1978 and 1997, suggesting that the terrane to the *north*, which includes virtually the entire breadth of the western Transverse Range, rose as well.

### Past Leveling and Future GPS

The central conclusion to be drawn from this study is that aseismic, vertical displacements are occurring in at least parts of the western Transverse Ranges that are arguably tectonic. This is certainly not surprising to anyone who has investigated the abundant geomorphic and geologic evidence for vertical tectonics in the Santa Barbara and Ventura areas. It is impractical to measure all vertical displacements in all parts of the western Transverse Ranges or even just in the Ventura basin by precise leveling survey even given its advantage of high precision. But it is quite practical to make repeated point surveys of parts of the region by GPS over time. Many measurements have already been made, but a systematic campaign to obtain GPS measurements on points of eventual geologic, seismologic, and geodetic interest should be intensified on their own merits, not just because they happen to lie near population centers. At the rates documented in this report, confident determinations of vertical displacements could be obtained in just 15-20 years by GPS, if not sooner, as the errors in vertical GPS decrease as they become better understood.

**Future Studies**

Until the time when we can count on GPS to yield vertical data with as little uncertainty as horizontal data, it is imperative to link the leveling data of the past to the GPS data of the future by surveys combining simultaneous measurements done by precise leveling, GPS, and absolute gravity. Not only will such an ambitious undertaking provide a temporally lengthy record that is more representative of geologic time, but it will also make a major contribution to analysis of errors inherent in all three independent measurement systems. This undertaking need not cover every single part of the western Transverse Ranges; a few select profiles would constitute main lines of reference that future GPS surveys can tie to. In fact only a handful of such profiles of repeated leveling measurements of sufficient quality actually exist across the Transverse Ranges. Each follows a major highway or railroad, and some were initially surveyed in the early 1900s, others in the early 1930s. None is plagued by the uncertainties of the effects of subsidence from withdrawal of fluids as posed by the Ventura Avenue oilfield. The measurement data are readily available for all of the profiles, and errors inherent in leveling are well understood and can be removed with some confidence from old data.

Such an endeavor will pay enormous dividends for future studies of tectonics and strain partitioning. Those of us today lament that more and more careful surveys were not done for tectonic purposes 100 years and so would be available for our use today. Of course it is a matter of technology, and today's technology will undoubtedly be eclipsed by that 100 years from now if, in fact, society and scientific curiosity are not eclipsed first.

# TECHNICAL REPORT, FINAL

## Strain Partitioning in Los Angeles-Ventura Region, Southern California: Evidence from Precise Leveling across Active Folds

by

Arthur G. Sylvester

Institute for Crustal Studies and

Department of Geological Sciences

University of California, Santa Barbara

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## Strain Partitioning in Los Angeles-Ventura Region, Southern California: Evidence from Precise Leveling across Active Folds

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Arthur G. Sylvester
Department of Geological Sciences, and
Institute for Crustal Studies
University of California
Santa Barbara, California 93106-9630
(805) 893-3156
e-mail arthur@magic.ucsb.edu

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Abstract: Comparison of three first-order leveling surveys across Ventura Avenue anticline indicate that five bench marks on its crest increased from 10 to 40 mm in 19 years relative to its flanks, despite continued pumping of oil and water from the anticline. The cumulative seismic moment of all earthquakes in and near the anticline in those 19 years scarcely exceeds the equivalent of a M4 earthquake, which, if it occurred at the 12-16 km depths where the hypocenters are located, would be sufficient to cause only 10 mm of surface uplift. The five bench marks lie above an active oil field, suggesting that the height changes among the bench marks may be nontectonic due to injection of water that exceeded the volume of produced oil and water between 1980 and 1987. After 1990 the proportion of injected water was less, but the height change still increased at the same rate (2 mm/yr) even as it has been during at least the past 80,000 years. The location of the height changes at the crest of the anticline, their observed rate of change, and their positive sign, together with the general observation that subsidence, not uplift, happens above active oil fields, are permissive evidence that the observed height changes are tectonic. Relative to the contemporary 6-8 mm/yr horizontal shortening across the Ventura basin, the 1-2 mm/yr height change across the Ventura Avenue anticline suggests that from 10 to 20% of the regional crustal shortening is being released locally in the anticline as aseismic uplift. It is simplistic to conclude that such partitioning of strain thus decreases the size or frequency of future earthquakes by the same percentage, however, because the 19 year sample is small both temporally and areally for this part of the western Transverse Ranges.

Non-Technical summary: We compared three first-order leveling surveys across Ventura Avenue anticline made in 1978, 1991, and 1997 to determine if the anticline has grown in that time period. That comparison shows that that five bench marks on the anticline's crest did rise from 10 to 40 mm in 19 years relative to its flanks, despite continued pumping of oil and water from the anticline. The cumulative energy released by all earthquakes in and near the anticline in those 19 years scarcely exceeds the equivalent of a M4 earthquake. If that earthquake had occurred at the 12-16 km depths where the hypocenters are located, then only 10 mm of surface uplift would have resulted. The rise of the five bench marks may be nontectonic due to injection of water that exceeded the volume of produced oil and water between 1980 and 1987, but the overall rate of uplift in that time was the same (1-2 mm/yr) as it has been during at least the past 80,000 years. Relative to the contemporary 6-8 mm/yr horizontal shortening across the Ventura basin determined by GPS measurements, it is tempting to conclude that that from 10 to 20% of the regional crustal shortening is being released locally in the anticline as aseismic uplift. It is simplistic to conclude that such partitioning of strain thus decreases the size or frequency of future earthquakes by the same percentage, however, because the 19 year sample represents such a part of the western Transverse Ranges, and the 19 year observation period represents such a short part of the 80,000 to 200,000 part of the anticline's history.